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THERMAL AND COST GOAL ANALYSIS FOR PASSIVE SOLAR HEATING DESIGNS*

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ABSTRACT

Economic methodologies developed over the past several years for the design of residential solar systems have been based on life cycle cost (LCC) minimization. Because of uncertainties involving future economic conditions and the varied decision making processes of home designers, builders, and owners, LCC design approaches are not always appropriate. To deal with some of the constraints that enter the design process, and to narrow the number of variables to those that don't depend on future economic conditions, a simplified thermal and cost goal approach for passive designs is presented. Arithmetic and graphical approaches are presented with examples given for each. Goals discussed include simple payback, solar savings fraction, collection area, maximum allowable construction budget, variable cost goals, and Btu savings.

INTRODUCTION

Over the past several years, standardized methodologies have evolved for the analysis and economic optimization of solar hot water and residential space heating designs [1]. In most instances, the optimizing criteria has been the minimization of life cycle costs (LCC): that is, determine the particular system configuration that results in the lowest delivered cost of heat to the home (solar and backup) over the expected system lifetime. Although it is widely held that life cycle cost minimization results in the specification of an economically efficient solar design [2], there are a variety of considerations that make the results of such optimization techniques untenable and/or unuseable.

- The results of economic design optimization are generally driven by expectations concerning unknown or uncertain future conditions; these expectations take the forms of specified values for parameters such as inflation rates, fuel and tax escalation rates, discount rates, and operation and maintenance costs over time. The uncertainty of parameter values increases as the life cycle analysis period increases.

- LCC analysis usually considers the stream of costs and benefits over the expected system lifetime. Where the building ownership period is equal to or greater than the expected system lifetime, as in government owned and operated buildings, this presents no problem. Where ownership periods are shorter, as with residential property, the solar system may change hands many times. This complicates life cycle analysis because of such questions as transaction costs, uncertain resale valuation, and changing owner/system interactions. An alternative approach is ownership cycle costing, OCC, which considers costs only throughout one ownership.

- LCC analysis embodies the cycle-implicit assumption that longer term benefits of LCC minimizing designs will be realized by the party making the analysis. Where the client/owner may also be the owner/operator (i.e. commercial buildings) the longer term benefits of design optimization will be realized by the requesting client. At the other end of the spectrum is the speculative tract-home builder of residential construction. These builders are not responsible for the ultimate operating costs of the homes they construct and therefore have no incentive to increase first costs with solar designs when a lower LCC for heating would result. Building codes and local ordinances mandating prescriptive construction standards and use of solar have been used to help circumvent these problems. On the other hand, when energy conservation and solar features are recognized as effective home marketing devices, the builders will respond to this demand with construction techniques that more closely represent optimized economic designs.

- Finally, an optimized LCC design may imply physical attributes that violate existing design, site, or budget constraints. Examples would be maximum lot frontage dimensions with sideyard set back conditions that limit the south-facing linear exposure and hence collection area; partial shading due to permanent or temporary obstructions; architectural styling considerations and restrictive covenants; maximum permissible housing costs in an area due to the predominance of non-solar market comparables, etc.

In response to these considerations, we have formulated a simplified approach that allows one to either graphically or arithmetically evaluate thermal and cost goals for residential passive solar heating designs with or without regard to LCC. In this particular consideration, economic optimization per se is not considered; rather we have presented an approach that allows for separation of current versus future parameters in order to identify specific thermal and cost conditions that are required to achieve a variety of specified conditions.

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ARTHMETIC APPROACH

The arithmetic approach to thermal and cost goals analysis is merely the algebraic equivalent of what will be shown graphically. Although accuracy is improved, the arithmetic approach is not as fast in application but is quite easily understood.

We begin with an equation that is equivalent to saying that the life cycle savings of a passive solar addition are exactly equal to zero, that is:

$$[SSF \cdot P_o \cdot PWF_f \cdot CRF \cdot LOAD \cdot DD \div 10^6] - [VC \cdot A \cdot PWF_s \cdot CRF] = 0 \quad (1)$$

The units of the two terms in brackets are in equivalent annual \$/yr. The first term represents annualized savings, the second term annualized costs. Definitions of terms is provided below:

- **SSF** Solar Savings Fraction which bears a direct relationship to the Load Collector Ratio (LCR) as set forth by LASL's Solar Group [3].
- **P_o** Initial cost of fuel in \$/mmBtu corrected for conversion efficiency.
- **DD** Average annual heating degree days (65°F Base)
- **LOAD** Heat loss factor of the residence for all surfaces other than the south facing passive solar collector area. (Btu/DD)
- **VC** \$/ft^2 variable cost of passive solar construction—fixed costs are seldom a significant factor in passive solar designs—all costs are expressed in the VC term.
- **A** Passive solar collection area (ft^2)
- **LCR** Building load collector area ratio (LOAD÷A) (Btu/DD-ft^2)
- **PWF_f** Present worth factor for auxiliary heat fuel costs which accounts for the future fuel escalation rate, discount rate, and period of analysis.
- **CRF** Capital recovery factor used to convert an initial dollar amount (present value dollar amount in our example) into a stream of equal annual payments such that the discounted sum of these payments is equal to the initial dollar amount.
- **PWF_s** Present worth factor for solar costs used to convert the initial passive solar construction cost into the sum of discounted annual cash flows associated with passive solar system ownership. PWF_s accounts for the down payment, principal plus interest payments, mortgage interest tax deductions, property taxes and deductions, insurance, operation and maintenance expenses and resale value net of the remaining loan balance.
- **SPBK** Simple payback equal to add-on cost divided by first year dollar savings.

$$SPBK = \frac{VC \cdot A \cdot 10^6}{P_o \cdot SSF \cdot LOAD \cdot DD}$$

Separating equation (1) into current and future factors:

$$\frac{VC \cdot A \cdot 10^6}{P_o \cdot SSF \cdot LOAD \cdot DD} = \frac{PWF_f \cdot CRF}{PWF_s \cdot CRF} = \frac{PWF_f}{PWF_s} \,. \quad (2)$$

Equation (2) still represents the breakeven LCC condition. The form of equation (2) has the advantage that the left side term deals with current factors (variable construction costs, initial fuel cost, degree days, and the three components of passive solar thermal performance represented by the LASL LCR tables; SSF, A, and LOAD). The right hand side deals with the future factors. In addition, the left side term is equivalent to the most basic definition of simple payback SPBK—first cost divided by the first year dollar savings.

DEFINING THE GOALS

In the context of equation (2), a variety of criteria may be used to determine system specifications or cost and thermal goals. Some of the criteria might include:

- simple payback
- solar savings fraction
- maximum add-on budget for passive solar construction
- passive collection area
- maximum energy budget. (e.g., Building Energy Performance Standards)

Other economic criteria have been used [4] to represent conditions necessary for consumer acceptance and relate to cash flow performance. These include years of negative annual cash flow and number of years required for cumulative savings to recover the initial downpayment expense. Since year by year cash flow analysis of any particular design is required to arrive at these numbers, they are not easily calculated using the approach set forth in this paper.

Equation (2) can be used in the following way:

a) Given values for DD and SSF(LCR); calculate SPBK or VC or P_o given values for two of the three.

b) Given values for SPBK, VC, P_o and DD, calculate SSF · LCR. Since SSF and LCR are mutually dependent, one must use the LCR tables to find the combination that yields a product close to the above value.

c) Given SPBK, SSF, and DD; A or LOAD can be determined given a value for the other; then P_o or VC can be determined given a value for the other; note SPBK, P_o, and VC may be interchanged in this process.

EXAMPLES

To exemplify (a), (b), and (c) above, assume we are looking at a double-glazed direct gain passive solar design in Dodge City, Kansas, with R-9 night insulation and mass surface/glazing area ratio of

3:1. From the LCR tables [3] we have the following performance relationship between SSF and LCR.

SSF	.1	.2	.3	.4	.5	.6	.7	.8	.9
LCR	236	109	68	47	35	26	20	14	8

From local data we know:

DD = 5046

P_o = \$.05/kwh = \$14.65/mmBtu (electric resistance)

a) Find the maximum variable cost one can pay for passive solar to achieve a six year payback for a .60 solar savings fraction against an electric resistance heating fuel alternative. From equation (2):

$$\frac{VC \cdot 10^6}{P_o \cdot SSF \cdot LCR \cdot DD} = SPBK \quad \text{or}$$

$$VC = \frac{SPBK \cdot P_o \cdot SSF \cdot LCR \cdot DD}{10^6}$$

Therefore,

$$VC = \frac{6 \cdot 14.65 \cdot .60 \cdot 26 \cdot 5046}{10^6} = \$6.92/ft^2$$

b) Find the thermal performance required to achieve an eight year payback for a direct gain design costing \$16/ft² against the electric resistance fuel alternative.

From equation (2):

$$SSF \cdot LCR = \frac{VC \cdot 10^6}{P_o \cdot DD \cdot SPBK}$$

$$= \frac{16 \cdot 10^6}{14.65 \cdot 5046 \cdot 8} = 27$$

The LCR table indicates that at SSF = .10, LCR = 236, and SSF · LCR = 23.6. Larger SSF values imply smaller product values, so the goal can only be met by a low-level passive design where the first square feet of collection area are the most efficient on a per square foot savings basis (i.e., the LCR value is over 236 Btu/DD-ft²).

c) Find the collector area necessary to provide a solar savings fraction of .30, with a building load of 10,000 Btu/DD. With a VC = \$15/ft² find the simple payback of such a design against the electric resistance heating alternative. For SSF = .30, LCR = 68, and

$$A = \frac{LOAD}{LCR} = \frac{10,000}{68} = 147\ ft^2.$$

$$SPBK = \frac{15 \cdot 10^6}{14.65 \cdot .30 \cdot 68 \cdot 5046} = 9.9\ \text{years}$$

GRAPHICAL APPROACH

Figure 1 illustrates the reference graphs for thermal and cost goal analysis. The figure is divided into five contiguous quadrants numbered I thru V. The lower left hand corner shows the units for each of the variables.

Quadrant I shows the relationship between average cost (AC), initial fuel price (P_0), and simple payback (SPBK). By defining two of these variables, the third is uniquely determined. Quadrant II shows combinations of average cost (AC) and annual heating season Btu savings per square foot of passive collection area (SSF · LCR · DD ÷ 10^3) that imply equivalent passive solar variable construction costs (VC). Again, if two of these three variables are known, the third is uniquely determined. Quadrant III accounts for heating degree days. Once degree days are specified a transformation can be made between seasonal square foot energy savings and energy savings per square foot per degree day (SSF · LCR). Although there are many algebraic combinations of LCR and SSF that would produce a given value of their product, only unique combinations of SSF and LCR are feasible for a passive design in a particular climate. This can be seen by examining the LASL LCR performance tables. In quadrant IV, the SSF-LCR performance combinations can be plotted for a particular design or designs. This is done by choosing a solar savings, fraction value, say SSF = .30, and finding the intersection of the corresponding LCR value (LCR = 68 for our direct gain example) and the SSF = .30 ray emanating from the origin. If this is done for all values of SSF from .1 to .9, and the points are connected, a feasible combination curve between SSF · LCR and LCR will be traced. This is shown in Quadrant IV. Finally, Quadrant V allows one to separate LCR into the LOAD and A components. This is useful for determining the impacts of various collector area building load combinations or for working backwards to find collector area or building heat loss requirements.

For illustration, the counterpart of example (c) in the arithmetic section is shown in Figure 1. The numbers in parentheses (1) thru (7), correspond to the sequence in steps when using the graphical approach. These are described in order below.

(1) As described above, plot the performance combinations for the double glazed direct gain design under consideration. Trace the resultant curve.

(2) Find the collector area necessary to provide SSF = .30 with LOAD = 10,000 Btu/DD by drawing a line from the feasible curve intersection point in QIV straight down to the LOAD = 10,000 curve in QV.

(3) Now draw a horizontal line to the left and read the intersection point off of the A axis. A = 147 ft² is the result.

(4) Now go back to QIV and draw a horizontal line from the SSF = .30 intersection point to the left into QIII. Continue the line until it intersects the proper DD value. If the DD

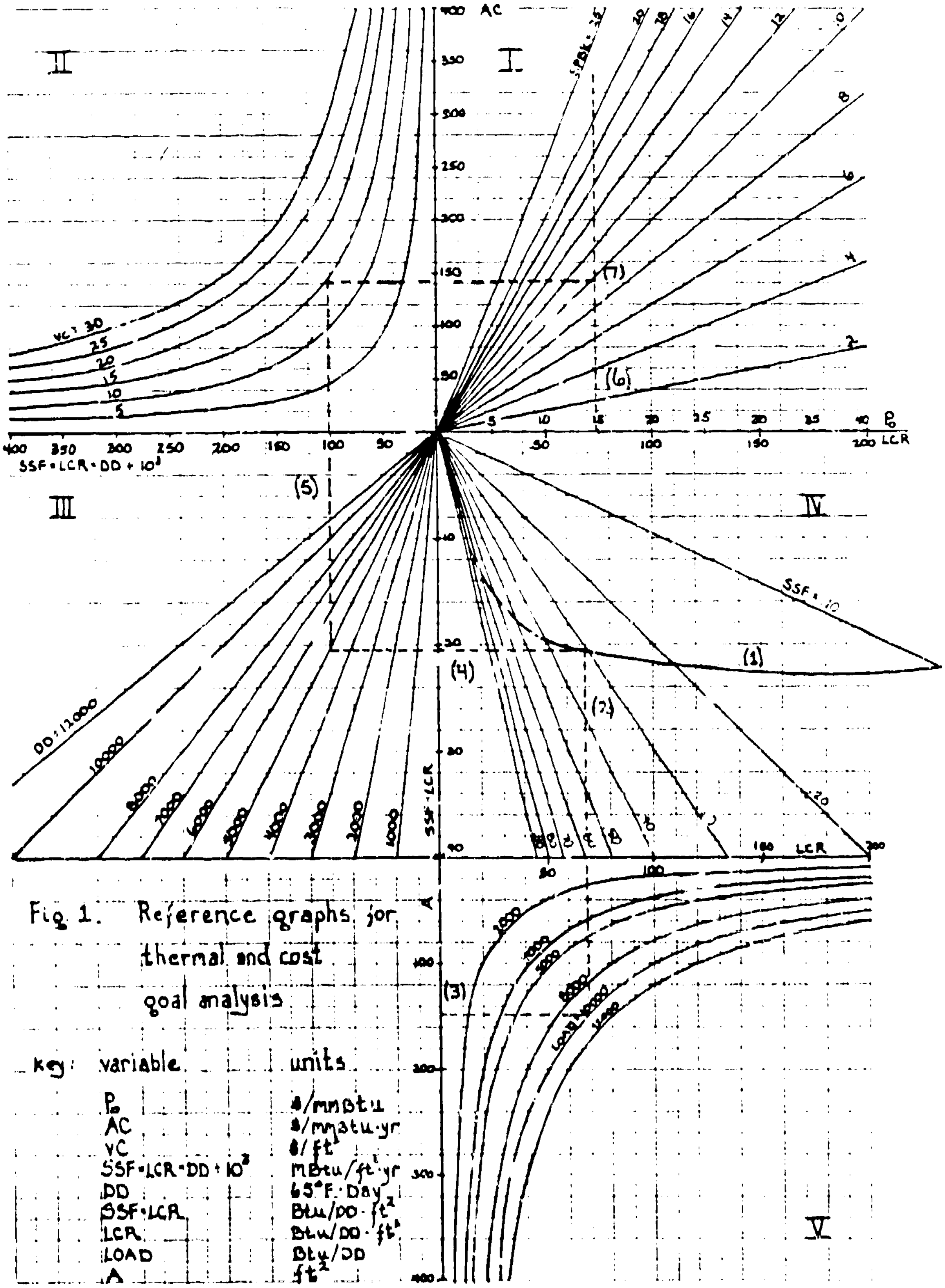

Fig. 1. Reference graphs for thermal and cost goal analysis

key:

variable	units
P_o	\$/mmBtu
AC	\$/mmBtu·yr
VC	\$/ft²
SSF·LCR·DD ÷ 10³	MBtu/ft²·yr
DD	65°F·Day
SSF·LCR	Btu/DD·ft²
LCR	Btu/DD·ft²
LOAD	Btu/DD
A	ft²

condition falls between the given lines interpolation is necessary.

(5) Next, draw a vertical line from the intersection in QIII into QII until it intersects the correct VC value. In this example go to the curve VC = $15/ft^2.

(6) Find the initial auxiliary fuel cost on the P axis in QI. Draw a vertical line straight up from that point. Electric resistance in Dodge City is $14.63/mmBtu is shown in QI.

(7) Draw a horizontal line from the correct VC point in QII (determined in (5)) into QI and find where the two lines intersect. This final intersection point determines the simple payback condition for the direct gain design under consideration. SPBK is shown to be a little bit less than 10 years which corresponds to the arithmetic results of 9.9 years.

The remaining (a) and (b) examples can be tested graphically by the reader. The accuracy of the graphical approach is not extreme, however it can be used with a minimum of effort and does not require arithmetic manipulation.

EXTENSIONS

Several extensions of the graphical approach can be made which might increase the usefulness and versatility of the method. First, the right side of equation (2) shows the ratios between the present worth factors for solar and auxiliary fuel. Another graph can be added that shows combinations of key financial parameter values that would yield particular PWF ratios. For example, two important parameters that can be analyzed are the ownership period and a resale profit factor that takes into account the relative appreciation rate of passive solar homes as compared to conventional market comparables. The limitation of this approach is that all other parameters entering the PWF formulas must be held constant to limit the problem to two dimensions. If the PWF ratio is divided by the SPBK of a particular design, the result will be a life cycle (or ownership cycle) benefit/cost ratio. Values greater than 1 indicate positive savings while values less than 1 indicate negative savings.

It also might be possible to integrate Balcomb's methodology [5] of optimal budget allocation between passive and conservation under various budget constraints. Derivative values of the LCR performance moves are available [3] to pursue this approach.

In conclusion, this paper has presented a simplified arithmetic and graphical approach for the analysis of passive solar heating design thermal and cost goals. The approaches have been shown to be consistent in application and offer the designer a means for quickly evaluating the implication of various design, performance, and economic criteria that may arise as constraints or goals to be met.

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